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14. ABSTRACT
The program intent was to demonstrate a progression over time in both the emergence of TE materials with improving performance and the state of the art in TE generator (TEG) design, also reflected in increasing performance. This progressive demonstration was to be achieved by building and operating two TEs in sequence, with each incorporating state of the art TE materials at the time of each build. A first TEG was designed and built with the following characteristics. The measured open circuit voltage of 8V at 600°C of the TEG matches well with the design target for the three segmented p-n couple used in this design. The peak power output at 600°C is 9.8W, which is slightly less than the projected power output of 11.5W based on the couple level testing derived from data shown in Figure 2. The most probable reason for this discrepancy is the higher internal resistance of the fabricated generator made from 32 couples compared to the resistance of individual couples. Maximum observed efficiency of this prototype generator at 600°C is 9.8W output/110W input = 8.9% versus the target of 14% at 700°C, temperature limited by cartridge heater capacity.

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Abstract

Thermoelectric generator efficiency is one of the key metrics for assessment of technology viability in particular applications. It provides an important indication of the progress made in development of thermoelectric materials having improved performance compared to state of the art materials. BSST has conducted a worldwide survey of thermoelectric material development efforts, identifying and sampling the most promising developments. These materials were assessed by their assembly and incorporation in demonstration power generation devices. Experimental methods were employed to assembly device components consisting of multiple types of thermoelectric material to optimize performance. Experimental generator designs were developed and employed to incorporate the thermoelectric components and provide a demonstration of the best possible performance that could be obtained from the materials selected. Bulk segmented materials were used in both n- and p-legs of tested couples and prototype generators. A compact cylindrical TEG, comprised of an axial heat source (electrical heater in a demo device), radial segmented TE elements, and a cold side with air or water cooling was developed and used to demonstrate material performance. The inner volume of the device operated in an Argon atmosphere. The design was adaptable to a variety of practical heat sources.

A portable test setup was developed to demonstrate device operation and assess the power generation capacity and efficiency. Results of couple-level and device-level testing were presented and compared to simulations based on known material properties. The program intent was to demonstrate a progression over time in both the emergence of TE materials with improving performance and the state of the art in TE generator (TEG) design, also reflected in increasing performance. This progressive demonstration was to be achieved by building and operating two TEs in sequence, with each incorporating state of the art TE materials at the time of each build. A first TEG was designed and built with the following characteristics. The measured open circuit voltage of 8V at 600°C of the TEG matches well with the design target for the three segmented p-n couple used in this design. The peak power output at 600°C is 9.8W, which is slightly less than the projected power output of 11.5W based on the couple level testing derived from data shown in Figure 2. The most probable reason for this discrepancy is the higher internal resistance of the fabricated generator made from 32 couples compared to the resistance of individual couples. Maximum observed efficiency of this prototype generator at 600°C is 9.8W output/110W input = 8.9% versus the target of 14% at 700°C, this temperature not achieved due to difficulties with the electrical cartridge heater power density. As project funds were exhausted at this point and availability of high performance TE materials was not immediate, the project was ended. TEG design approach fundamentals, performance characterization of the initial TEG components, and a path forward have been captured as products of this project.

Technical Objectives

Year 1 Project Objective

Design, build, and demonstrate a 14% efficient thermoelectric generator (TEG) with a power output of at least 20 watts, at BSST's facilities.

Supporting Technical Objectives:

1. Source and validate advanced thermoelectric materials that are viable candidates for use in the TEG.

BSST will continuously solicit thermoelectric (TE) power generation materials from academic, laboratory, and industrial sources. BSST will test samples to evaluate material suitability to meet project goals. Feedback will be provided to material vendors with an emphasis on identifying and resolving critical issues to enable the usage of promising materials. In some instances, BSST may source advanced materials from abroad.

Work required to achieve this objective is interactively related to that of other objectives of the project. Ongoing information exchange is anticipated between material experimental testing, interfacial properties experimental testing, and system modeling.

The intended flow of work by quarter to achieve this objective was:

Q1 – Samples of candidate materials will be obtained and available in house. Preliminary testing of thermoelectric and physical properties will be performed. For initial verification experiments, the form factor of samples need not be that which is necessary for the final build, but rather in forms that material vendors can readily provide. Thermal conductivity, electrical conductivity, Seebeck coefficient, and coefficient of thermal expansion will be measured as a function of temperature. In the case of metallized samples, the contact resistance will be measured either indirectly by fitting performance test data, or directly by using a scanned probe measurement setup. The materials will be assessed for their suitability for use in power generation devices, and the data will be compared to those provided by material suppliers. Measurement results will be used in the TE stack model to provide further refinement of the modeling simulation of specific materials.

Q2 – Samples of all materials chosen for system integration will be obtained and available in house in form factors that will be determined from material properties and BSST's design requirements. Prototype segments/cascades will be assembled and tested for power generation capabilities as a function of temperature and output current. Thermal power input and efficiency of the total stack will be measured; efficiency of individual stages will be extracted from data fitting, and compared to predicted values. If deviations between measured and predicted values are larger than 5%, and a material is a promising candidate for the design, further analysis will be conducted to resolve the discrepancies.

Q3 – Materials selected for use in the TEG will be obtained and available in house in sufficient quantity to build the demonstration 20W output TEG deliverable. The amounts of the materials required will be determined by the system model, upgraded to incorporate the results of earlier testing within this task. BSST will acquire at least double the amount of the material that is required for a single generator build, to accommodate contingencies. Below is a summary of predicted material volumes needed for the candidate material system under consideration. A more refined set of material requirements will be formulated based on the results of the earlier work under this objective.

Material	Volume used for at least 20 W, 14% demo, cm^3	Minimum volume required in house, cm^3
$CeFe_4Sb_{12}$	0.57	1.2
TAGS	0.30	0.60
Bi_2Te_3	0.34	0.68
$CoSb_3$	0.70	1.40
LAST	0.52	1.04
Total TE material used:	2.43	

2. Design an optimized thermoelectric stack, the core building block of the TEG.

Parallel to material sourcing efforts, BSST will design and optimize the structure of segmented TE stacks that will enable achievement of the 14% efficiency goal for Year 1. The model will use as inputs: material properties, interfacial properties, form factors of individual segments, and area and length ratios of p- and n-type materials. Work performed to achieve this objective will be closely coordinated with other tasks in Year 1 because of the iterative nature of information exchange between experiment modeling.

The intended flow of work by quarter to achieve this objective was:

Q1 – TE material data will be obtained from materials suppliers. Data will include electrical and thermal conductivities and Seebeck coefficient over appropriate temperature ranges, and will be imported into BSST's model. A baseline design will be produced by optimizing cross sectional area, thickness, heat flux and electrical current for each segment and cascade. The baseline design will enable at least 14% efficiency with no more than 12% of heat lost to pathways outside of TE material. The output power of the baseline design will exceed 20W. The efficiency of the baseline design will be analyzed as a function of hot and cold side temperatures. The hot side temperatures will range from 500°C to 700°C, and the cold side temperatures will range from 30°C to 50°C. BSST will determine what fraction of this design space will yield TEG efficiency of at least 14%. Design parameters will be modified to maximize this fraction.

Q2 – An updated model will be completed and will incorporate BSST measurement data collected from the advanced TE material samples obtained in pursuit of the first objective. The output of the model will be used to determine the final geometry of the TE elements and segments. The results will be used as inputs to material vendors to enable reaching the Q3 material availability milestones of the first objective, and to assure that the material system will be capable of operation over the projected temperature range to be used in testing in pursuit of achieving the fifth objective, demonstrating a 14% effective TEG.

3. Reduce interfacial losses within the designed thermoelectric stack to support achievement of the TEG efficiency goal.

BSST will measure the interfacial electrical resistance and integrity of metalized TE materials delivered by vendors. In cases where material vendors provide un-metalized materials, and the materials are attractive candidates for use in TEGs, BSST will engage internal and external resources to develop suitable metallization and bonding solutions.

The intended flow of work by quarter to achieve this objective was:

Q1 – Results of testing the advanced TE materials sourced and the TE stack design will be used to develop acceptable contact/interface resistance specification values (preliminary calculations indicate this value to be nominally 1.0 $\mu\Omega cm^2$ for electrical contact resistance). Candidate segment and cascade interfaces, expected to meet contact resistance requirements, will be chosen. Experimental measurement and verification of interfacial contact resistance will start.

Q2 – Contact resistance performance of chosen materials will be completed. Test results will be fed back into the simulation activity support the second objective, establishing the design of an optimized TE stack. Assembly methods of the TE stack will be down-selected and documented.

Q3 – Sample TE stacks will be assembled. Bonding quality will be tested by thermocycling from room temperature to maximum operating conditions for a minimum of 100 cycles. Ability to meet performance targets after cycling will be assessed.

4. Reduce interfacial losses of components outside of the thermoelectric stack to support achievement of the TEG efficiency goal.

BSST will analyze electrical, thermal, and mechanical constraints on the TEG design operating with hot side temperatures from 500°C to 700°C and cold side temperatures from 30°C to 50°C. Similarly to the analysis of interfacial properties with the stack (Task 1.3), the metrics for acceptable electrical and thermal interfacial resistances will be determined. Mechanical constraints due to potential CTE mismatches between the TE materials and the hardware outside the TE stack (i.e. hot side shunts and hot side heat exchangers) will be evaluated. Solutions will be developed to mitigate any significant CTE mismatch issues identified.

TE material CTE and temperature stability properties will be used to develop design choices and processes for system assembly. Specifically, bonding processes will be evaluated to assure that TE materials are not exposed to temperatures exceeding allowable values, so as to avoid structural and/or TE property degradation under operation. Candidate assembly processes will be checked for compatibility with TE materials capabilities.

The flow of work to achieve this objective is an integral part of the work performed in pursuit of the third objective with a focus on non-TE stack components, and follows the same timing.

5. Design, build, and demonstrate a 14% efficient TEG.

Based on the knowledge gained in achieving the previous objectives, BSST will apply the chosen engineering solutions and assembly processes to design a practical demonstration TEG. The TEG will be constructed from materials chosen in the previous work. The device will be built and demonstrated to ONR representatives at BSST at the end of Year 1.

The intended flow of work by quarter to achieve this objective was:

Q3 – Based on the results of the simulation and TE stack design work, and bonding investigations performed in the course of reducing interfacial losses, the generator system will be designed around the chosen TE stack geometry. The design will include:

- cartridge heaters of adequate power and temperature rating,

- hot shunt geometry, materials and finishing,
- TE attachment methods,
- cold shunt geometry, material and finishing,
- thermal insulation materials and their application methods,
- cold side heat exchanger design,
- thermal and electrical in-situ diagnostics locations, and
- measurement instrumentation specifications.

Mechanical drawings of custom parts will be produced. Off the shelf components will be specified.

Q4 – Custom parts will be manufactured. Off the shelf components will be procured. TE material to be used will be that obtained during the initial TE material sourcing and validation. The TEG will be assembled and placed in an inert atmosphere (glove box). The TEG will be tested to verify at least 14% efficiency and at least 20W of electrical power output. Testing will be conducted with the hot side between 500°C and 700°C, and the cold side between 30°C and 50°C. The generator will be thermocycled at least 10 times between an operating point to be determined and room temperature. This testing, and a subsequent demonstration for ONR personnel will be conducted at BSST's facility in Irwindale, California.

Year 2 Project Objective

Design and build a packaged, portable 20% efficient thermoelectric generator system with a target power output of 40 watts, to be delivered to an ONR-designated laboratory for independent testing.

There are two major differences in the work required to meet this objective as compared to that of Year 1. To achieve 20% efficiency; a) higher ZT materials must replace conventional BiTe in the lower stage of the TE stack, and b) a portable, compact demonstration device that includes data acquisition electronics and LCD display, will be delivered, compared to the laboratory demonstrator to be delivered in Year 1.

Supporting Technical Objectives:

1. Obtain and test higher performing [than in Year 1] thermoelectric materials.

The composition of the TE stack will be changed from that developed in Year 1 to improve efficiency from 14% to 20%. Materials that perform successfully under Year 1 of the Project will be used in this phase. BSST will support material developers' efforts to continuously improve the properties of materials that we used in Year 1. Thick film materials (thickness at least 100 µm) will be investigated as potential high performing lower segment/cascade materials for the generator. The emphasis will be on making these materials available to the project, testing them, resolving any high interfacial resistance and metallization issues, and designing these new materials to operate optimally with other materials of the stack. The higher temperature (upper stage) materials will be reviewed for performance capability against new material candidates that have emerged from Year 1 material assessment activities.

The intended flow of work by quarter to achieve this objective was:

Q1 – Samples of candidate materials (new and/or improved compared to materials of Year 1) will be obtained and available in house, and preliminary testing of thermoelectric and physical properties will be performed. For initial verification experiments, the form factor of samples need not be that necessary for the final build, but rather may be in forms that material vendors can readily provide. Thermal conductivity, electrical conductivity, Seebeck coefficient, and coefficient of thermal expansion will be measured as a function of temperature. In the case of metallized samples, the contact resistance will be measured either indirectly by fitting performance test data, or directly by using a scanned probe measurement setup. The materials will be assessed for their suitability for use in power generation devices, and the data will be compared to those provided by material suppliers. Measurement results will be used in the TE stack model to provide further refinement of the modeling simulation of specific materials.

Q2 – Samples of all materials chosen for system integration will be obtained and available in house in the form factors that will be determined by the material properties and BSST's design requirements. Prototype segments/cascades will be assembled and tested for power generation capabilities as a function of temperature and output current. Thermal power input and efficiency of the total stack will be measured; efficiency of individual stages will be extracted from data fitting, and compared to, predicted values. If the deviation between measured and predicted values is larger than 5%, and the material is a promising candidate for the design, further analysis will be conducted to resolve discrepancies.

Q3 – Materials will be obtained and available in house in sufficient quantity to build the demonstration 20W output TEG deliverable. The amounts of the materials required will be determined by the system model, upgraded to incorporate the results of earlier testing within this task. To accommodate contingencies, BSST will acquire at least double the amount of the material that will be required for a single generator build. As a reference, below is a summary of predicted material volumes needed for the candidate material system under consideration. A more refined set of material requirements will be formulated based on the results of the earlier work under this task.

Material	**Material needs for at least 40 W, 20% demo**	**Minimum amount of material required in house**
	Bulk Materials. Volume, cm^3 (Note 1)	
$CeFe_4Sb_{12}$	0.12	0.24
TAGS	0.05	0.60
$CoSb_3$	0.02	0.04
LAST	<0.01	0.02
Total bulk TE material used:	~0.2	~0.9
	Thick Film Materials. Area, mm^2.	
QDSL at 100 μm thickness	65	200

Note 1: It is likely that less TE material will be needed in Optional Year 2 compared to Year 1 requirements because of two factors:

- *increased system efficiency, and*
- *increased heat flux density driven by the lower thickness of the thick film stage . The geometry of the rest of the TE segments will change to be compatible with the associated higher heat flux.*

2. Design an optimized TE stack to achieve the 20% efficiency goal of Year 2.

Parallel to material sourcing efforts, BSST will design the optimized structure of segmented TE stacks needed to achieve the 20% efficiency goal of this project period. The results of the Year 1 will be the baseline for this evaluation. Among the inputs to the model will be material properties, interfacial properties, form factors of individual segments, ratio of p- and n-type materials, and other parameters. This work in pursuit of this objective will be closely linked with that of the other Year 2 objectives because of the iterative nature of information exchange between experiment and modeling.

The flow of work by quarter to achieve this objective is:

Q1 – TE material data will be obtained from materials suppliers. Data will include electrical and thermal conductivities and Seebeck coefficient over appropriate temperature ranges, and will be imported into BSST's model. A baseline design is produced by optimizing cross sectional area, thickness, heat flux and electrical current for each segment and cascade. The baseline design will enable at least 20% efficiency with no more than 12% of heat lost to pathways outside of TE material. The output power of the baseline design will exceed 40W. The efficiency of the baseline design will be analyzed as a function of hot and cold side temperatures. The hot side temperatures will range from 500°C to 700°C, and the cold side temperatures will range from 30°C to 50°C. BSST will determine what fraction of this design space will yield TEG efficiency of at least 14%. Design parameters will be modified to maximize this fraction.

Q2 – An updated model will be complete and will incorporate the BSST measurement data collected from the materials obtained and tested at the beginning of Year 2. The output of the model will be used to determine the final geometry of the TE elements. The results will be used as inputs to material vendors to enable reaching the Q3 material availability milestones of Year 2, and assure that the material system is capable of operation over the projected temperature range specified for the 20% efficient generator design.

3. Design, build, and test a preliminary 20% efficient TEG prototype.

The preliminary TEG to be developed in meeting this objective will be a prototype device that does not encapsulate the TE device within the generator, and that will be designed, built and tested at BSST.

The flow of work by quarter to achieve this objective is:

Q2 – The design will be modified to accommodate the updated TE stack configuration. System components will be reviewed and redesigned to meet requirements for:

- higher thermal flux density,
- different temperature ranges for various segment stages,
- improved bonding techniques,
- potentially separate electrical circuits for cascades (this will require changes in the measurement setup as well), and
- the possible need for encapsulation at a later stage (i.e. design choices that are incompatible with encapsulation will be prohibited).

Mechanical drawings of custom parts will be produced. Off the shelf components will be specified, including cartridge heaters, cold side heat exchangers, control electronics, power supplies.

Q3 – Custom parts will be manufactured. Off the shelf components will be procured. TE material obtained during Year 2 materials evaluations will be available and used as appropriate. The TEG will be assembled and placed in an inert atmosphere (glove box) for testing and characterization. The TEG will be tested to verify operation with at least 20% efficiency and at least 40W electrical power output. The TEG will be thermocycled at least 10 times, to demonstrate operating stability and to assure that efficiency and power output have not degraded below 20% and 40W, respectively.

4. Package the 20% efficient TEG to allow shipment to and evaluation at an independent test location. Provide for encapsulation of the TE materials within the TEG to prevent damage by exposure to air while the TEG is operating.

During this task the encapsulation design for the 20% efficient prototype will be developed. At the end of the task, the device, and its monitoring display and support equipment, will be available for independent testing at a location chosen by ONR.

The flow of work by quarter to achieve this objective is:

Q3 – Packaging requirements will be specified. Packaging design will be developed. Sample packages will be produced and tested for thermal and environmental leaks and design stability, with a simulated TEG inside. Final mechanical drawings will be produced. Off the shelf components will be specified, including items necessary for the portable demonstration system (e.g. liquid bath, pumps, control electronics, power supply, and computer system).

Q4 – Custom parts will be manufactured. Off the shelf components will be procured and integrated into the system. The preliminary Year 2 prototype TEG developed will be packaged and sealed. Performance after packaging will be verified. Shipment conditions will be simulated, and performance will be verified once again. The TEG will be ready to be shipped to the test facility specified by ONR.

5. Prepare an analysis of the migration path of the TEG developed for integration into a military vehicle identified by the project's ONR program officer.

BSST will perform an analysis of potential applications of TEGs for specific military vehicle platforms. BSST will work with ONR, and also use its ongoing analysis of government and commercial applications for TEGs, to assess and identify attractive target applications. BSST will work with the ONR program officer to provide a preliminary design concept for possible integration of a TEG into a Navy (or other designated) military vehicle.

Technical Approach

Accelerating the Hand-off from Material Developers to System Integrators

Any delay between the time of material advancements by developers, and usage by system integrators, reduces the value of the material developer's contribution. A goal of this proposed program is to minimize the time from discovery, fabrication, and characterization of advanced TE materials in the laboratory, to their incorporation into devices. By actively contributing to the reduction of this time, the value of the materials research sponsored by ONR and other Government agencies will be maximized.
The structure of this project included specific tasks to accelerate this technology transition. We have the capability of starting with TE materials in the shape of raw thick film and ingots, and metalizing, terminating, shaping, and processing the materials into TE elements. We take the elements and form

devices, and make all of the necessary material and device-level TE properties and efficiency measurements. We make small scale (two to four pellets) power generators for screening and diagnostic purposes. The information gained by making these small scale generators is used to measure system-level properties including TE material compatibility factors, interfacial thermal and electrical properties, and device stability and repeatability. We use models previously developed and upgraded as needed to develop our devices.

Several initiatives to accelerate TE material readiness were undertaken by BSST for diverse TE material developers. By these actions, BSST provided the material developer with timely critical performance feedback, independent property evaluation, and paths to make the materials most attractive to end users. Possibly most importantly, BSST was positioned to pull promising materials from the developer in a positive constructive process. By doing so, BSST provided a link from the developers to commercial opportunities that can result from early adoption of potentially viable materials.Generator Performance Projections with Advanced Materials

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A general view of the factors contributing to the TEG performance is presented in Figure 1. The proposed roadmap to achieve the goals of Year 1 Base and Year 2 Option are discussed below.

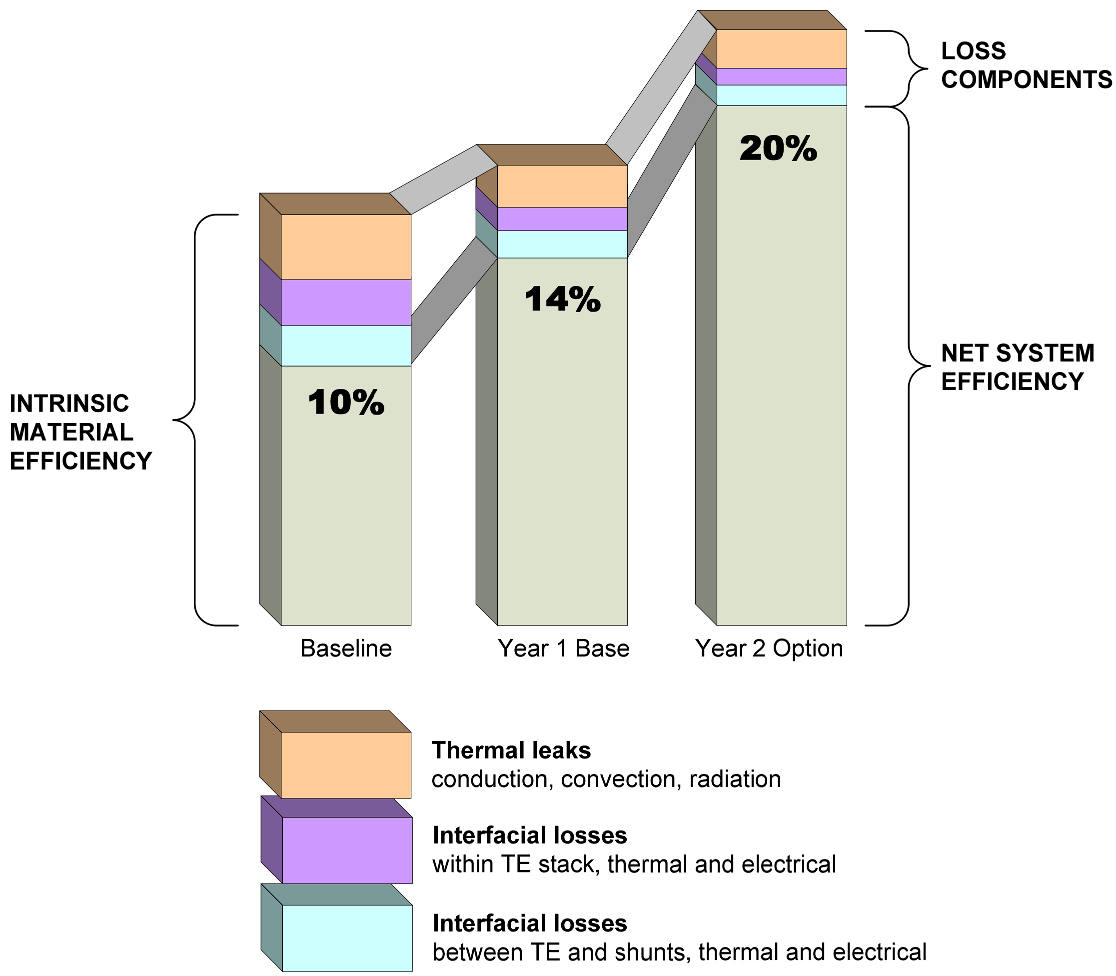


Figure 1. Factors contributing to the differences between intrinsic material efficiency and net system performance. The program goals are to derive maximum benefit of intrinsic material performance while minimizing parasitic losses.

Table 1 describes two of many possible design scenarios for achieving the 14% and 20% efficient TEGs. Several assumptions were used to develop these scenarios. For the 14% efficient generator, it is assumed that the interfacial resistance between two surfaces is 1.0 $\mu\Omega cm^2$. This includes the two external interfaces between the material and the connectors as well as the interfaces between segments of an element. In BSST's testing to date, interfacial resistances lower than 1.0 $\mu\Omega cm^2$ have been indirectly measured, making this a conservative estimate. It is also assumed that the amount of heat that is either lost to the environment, or through thermal leak to the cold sink, is approximated at 12%. In BSST's testing to date, heat loss values of approximately 20 – 25% have been indirectly measured. However, we believe that there is substantial room for improvement through better external insulation, more complete surface area coverage, reduced diagnostic wiring, reduced radiation from the hot surfaces, and reduced conduction losses by either using a vacuum environment or a gaseous environment with lower thermal conductivity (such as Xenon).

	Cascade/segment		Material	Hot side temperature,°C	Cold side temperature, °C	ΔT, °C	Element area, mm^2	Element thickness, mm	Net Efficiency, %
Year 1: BULK MATERIAL USED									
p-leg	Upper cascade		CeFe4Sb12	700	525	175	52.8	2.7	
	Temperature drop of 25°C between cascades					25			
	Lower cascade	Segment 1	TAGS	500	169	331	36	2	
		Segment 2	Bi2Te3	169	30	139	36	0.75	
	Total for p-leg					***670***		***5.45***	
n-leg	Upper cascade		CoSb3	700	525	175	64.8	2.7	
	Temperature drop of 25°C between cascades					25			
	Lower cascade	Segment 1	LAST	500	176	324	64.8	2	
		Segment 2	Bi2Te3	176	30	146	64.8	0.9	
	Total for n-leg					***670***		***5.6***	
	Upper cascade (p- and n-legs combined)								***2.34***
	Lower cascade (p- and n-legs combined)								***12.89***
	Device total*								**14.93**
Year 2 (Option): BULK AND THICK FILM MATERIAL USED									
p-leg	Upper cascade	Segment 1	CeFe4Sb12	700	500	200	38.5	0.98	
		Segment 2	TAGS	500	325	175	38.5	0.35	
	Temperature drop of 25°C between cascades					25			
	Lower cascade		QDSL PbTe	300	30	270	10	0.1	
	Total for p-leg					***670***		***1.43***	
n-leg	Upper cascade	Segment 1	CoSb3	700	492	208	10	0.53	
		Segment 2	LAST	492	325	167	10	0.11	
	Temperature drop of 25°C between cascades					25			
	Lower cascade		QDSL PbTe	300	30	270	10	0.1	
	Total for n-leg					***670***		***0.74***	
	Upper cascade (p- and n-legs combined)								***7.57***
	Lower cascade (p- and n-legs combined)								***14.13***
	Device total*								**20.63**

* Less than 100% of heat available for lower cascade due to conversion to electricity in the top cascade, therefore the total efficiency is not a direct sum of upper and lower cascade efficiencies

Table 1. Possible design options of 14% and 20% efficient generators. Bulk materials are used in the Year 1 notional design. High performance thick film materials are considered to be combined with bulk materials in Year 2. The segmentation and cascading is optimized to balance heat flows and to maximize the performance of each material system across the temperature range it is exposed to.

It was anticipated that the 14% generator would use p- and n- Bi_2Te_3 and skutterudites as well as p-type TAGS produced by Marlow Industries, or an equivalent such as Ames Laboratory. The n-type LAST material would be supplied by Michigan State University, or an equivalent. The TAGS and LAST materials were to be segmented with Bi_2Te_3 provided by Marlow by either hot pressing or through direct soldering. The direct soldering approach was previously used by BSST to achieve the 10% efficiency generator described above. BSST discussed availability of these materials with the material provider.

It should be noted that due to material incompatibility, the skutterudites cannot be directly attached to the other two segments. They were to be connected in a cascade arrangement to allow the cross-sectional areas of the high and lower temperature segments to be optimized, but would still be electrically connected through a thin layer of high conductivity metal. Thus, the same electrical current runs through the entire couple. A 25°C temperature drop is assumed for the cascade interface. In the example, the total temperature gradient for the couple is 670°C with a maximum hot side temperature of 700°C.

The 20% efficient generator design scenario uses some materials and techniques that are similar to that of the 14% generator. It was assumed that the interfacial resistance is improved to 0.1 $\mu\Omega cm^2$. This is more aggressive than what was assumed for the 14% generator but our tests (and those of JPL's described in Thrust Area 4, below) strongly indicated that for interface material systems under evaluation, interfacial contact resistance drops by a factor of 4 to 8 between room temperature and operating temperatures; making the desired reduction within the time frame of the Year 2 Option more probable. BSST had prototype materials with indirectly measured interfacial resistances of 0.2 $\mu\Omega cm^2$ at hot side temperatures of about 500°C. BSST also had prototype Bi_2Te_3 with 0.2 $\mu\Omega cm^2$ interfacial resistance that it expected to use in production parts in 2008. For the 20% efficient TEG, the heat loss assumption was also reduced to 10%. The p- and n- Bi_2Te_3 material would be replaced by MIT/Lincoln Lab-provided QDSL PbTe, or another high performance low range material. The MIT/Lincoln Lab material has a demonstrated maximum temperature of at least 300°C and is currently available in thicknesses up to 0.1mm. BSST expected to determine the actual upper operating temperature limit by stability and repeatability testing of the n- and p-elements. The thickness limitation present required low interfacial resistance as noted. We expected to facilitate the fabrication of low resistance interfaces in the early part of Year 2. We also expected to evaluate laminated samples with in-plane current flow, thereby allowing us to increase current flow length to two to three mm, compared to 0.1 mm for a cross-plane operation of the thick film.

Material compatibility complicates segmentation in the 20% efficient system. Skutterudite and TAGS/LAST materials were to be segmented together as described above while the QDSL PbTe was to be cascaded on the low temperature side to complete the couple. However, the two parts of the cascade could not operate at the same current advantageously, so they were to be electrically isolated from each other using a thin piece of high thermal conductivity ceramic such as AlN.

Other promising materials were to be be evaluated in Year 1 and Year 2 (Option) to achieve alternative paths to efficiency goals. The design analysis presented above assumed hot and cold temperatures of 700°C and 30°C, respectively, and included present known material properties. The intent of this modeling was to identify a promising candidate material system, but not to do an exhaustive study of all potential TEGs. For example, other materials such as Half-Heusler alloys could have been substituted for MSU's LAST material.

Further, the study results are shown for one pair of many hot and cold side temperatures that were considered as part of the program design definition. Other options for hot side operation from 500°C to 700°C were to be studied in combination with cold sides from 30°C to 50°C. BSST recognized that eventual target applications may require different hot and cold side temperatures. By modeling different temperature combinations, along with corresponding material combinations, boundary conditions for usage and efficiency would be developed. Additionally, BSST was to work with material suppliers to determine the most advantageous operating temperatures for materials. As examples, can the hot side temperature for QDSL PbTe and LAST material be extended? If so, can stages be eliminated and/or overall efficiency improved? Also, properties of materials may improve because of further composition or heat treatment refinements that occur during (and possibly as a result of) this program. BSST will use its knowledge in material analysis and modeling to encourage advancements in these areas, and use positive results to upgrade our designs.

Material options, coupled with hot side temperatures between 500°C and 700°C, and cold side temperatures between 30°C and 50°C, were to be investigated, tested as appropriate, and modeled in the early part of optional Year 2, to develop a range of high efficiency operational boundary conditions.

Factors Affecting Generator System Efficiency

Availability of high efficiency thermoelectric materials is the essential, but not the only, factor contributing to an efficient generator system. The materials need to be designed into a system that derives maximum benefit from the advances of materials while minimizing parasitic losses that degrade performance.

A general breakdown of factors contributing to system efficiency is presented in Table 2. The thrust areas of the proposed effort address both system optimization and loss reduction.

Factors affecting generator performance	**Proposed thrust areas**
Intrinsic material performance	Obtain the best materials Optimize stack design for compatibility
Thermal leaks: conduction, convection, radiation	Minimize exposed areas Suppress leaks by insulation/shielding
Interfacial losses within TE stack, thermal and electrical	Characterize contact resistance Develop metallization solutions Develop bonding solutions
Interfacial losses between TE and shunts, thermal and electrical	Investigate joining approaches

Table 2. Factors contributing to the efficiency of the generator and proposed thrust areas.

As a reference, Table 3 below outlines the contributions of individual loss mechanisms in the 10% efficient generator recently developed at BSST and discussed above.

	Loss (%)	**Net Efficiency (%)**
Ideal device efficiency	baseline	13.37
External thermal leaks (22.77%)	3.05	10.32
Interfacial losses between segments (0.32 $\mu\Omega cm^2$)	0.03	10.29
External interfacial losses (0.32 $\mu\Omega cm^2$)	0.06	10.23
Device net efficiency	n/a	10.23

Table 3. Loss components breakdown of the 10% efficient generator developed at BSST.

The first row of Table 3 shows the ideal efficiency for a segmented device made of 3 x 3 x 2 mm TAGS and PbTe segmented with 3 x 3 x 0.6 mm Bi_2Te_3 provided by Marlow Industries and operated for the particular condition of the cold and hot sides between -0.7°C and 494.3°C, respectively. With such thick elements, and such low interfacial resistance, the interfacial resistance loss mechanisms play a minor role for this device. However, the external thermal losses are substantial. Addressing the contributions to these losses will be a significant focus of the proposed effort, as noted below in Thrust Area 2. For other designs where the TE segments are thinner and interfacial resistances are higher, the interfacial resistance can play a large, or even a debilitating role (see Thrust Area 3 below, which addresses internal interfacial losses reduction).

Scope Definitions and Limits for the Program

The objective of BSST work was to concentrate on the system-level integration of the TEG components. Thermal source design and its integration with the TEG were beyond the scope of this project. Electrical cartridge heaters were to be used as a model thermal energy source, as they were suitable for careful accounting for power input and hence system efficiency.

The heat sink on the cold side of the TEG was to be either ambient air or a non toxic liquid such as water. The energy spent on coolant circulation was not to be accounted for in the system efficiency calculation.

Thrust Area 1: TE Materials

Advanced Materials Availability

BSST was to assess the practicality of each advanced material from the standpoint of system integration. BSST would then work to engage the chosen material developers to provide sufficient quantities of their materials for testing and system integration. Some of the groups/organizations that BSST intended to solicit materials from were:

- Northwestern University/Michigan State University (Prof. M. Kanatzidis/Prof. T. Hogan, see Appendix 1)
- Marlow Industries (Dr. J. Sharp, see Appendix 2)
- Caltech/JPL (Dr. J. Snyder, see Appendix 3)
- Ohio State University (Prof. J. Heremans, see Appendix 4)
- Tellurex
- Ames Lab
- MIT/ Lincoln Lab
- Ioffe Institiute (Russia)
- RTI
- Chinese sources

BSST perceived the material assessment and awareness as an ongoing task. The progress in the field was and is becoming more evident; therefore BSST's intentionwas to keep the possibility open for work with new parties/solutions that could emerge during the course of the program, and to assure that promising new candidate materials could be evaluated in Year 2 (Option).

TE Stack Design

BSST modeling tools were to be utilized to optimize both the structure of the segmented stacks and the ratio of p- and n-type materials to achieve the maximum performance benefit.

An example of such stack structure optimization is shown above in the Generator Performance Projection section. Recently, the BSST software suite was applied to analyze the 10% efficient generator with segmented n-type $PbTe/Bi_2Te_3$ and p-type $TAGS/Bi_2Te_3$ pellets. It was predicted that if the form factor of the pellets is the same for both types, then it is beneficial to have an uneven ratio of p- and n-type pellets (i.e. different total areas for the two types). Specifically, it was predicted that the efficiency would be maximized if the amount of n-pellets exceeds that of the p-pellets by a factor of 1.5 to 2.0. As a result of this prediction the generator was built with the n:p pellet area ratio of 1.5. This ratio leads to an efficiency increase from ~9% (in the case of an even ratio) to the above 10% for the optimized design.

Thrust Area 2: External Thermal Leak Minimization

In order to derive the maximum benefit of the material performance, BSST, as a system integrator, needed to ensure that the maximum possible percentage of the thermal power input flowed through the thermoelectric materials and not through the leakage paths. The module design goal was to minimize exposed areas of the thermal source and to reduce parasitic leaks (e.g. through diagnostic wires).

Remaining leak paths wee to be tackled with insulation against conductive and convective loss pathways, and with the incorporation of radiation shielding solutions. Possible approaches included:

- material barriers such as thermal blankets, glass bubbles and aerogels,
- encapsulation with high molecular weight gases (e.g. Xenon) or operation in vacuum, and
- advanced solids engineered towards dramatically reduced thermal conductivity.

BSST continued to throughout this project to work with the leading developers in the field to assess the viability of their solutions. Examples of such solutions included highly engineered solids with extremely low thermal conductivity (developed by Prof. Johnson at Oregon State University under a program funded by ONR), and castable aerogels impregnated with radiation scattering particles (investigated at the thermoelectric group in the NASA Jet Propulsion Laboratory).

Thrust Area 3: Internal Interfacial Losses Reduction

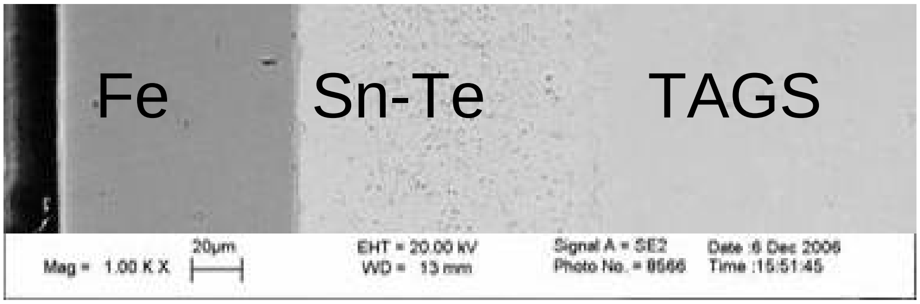
Low contact resistance of the electrical interfaces is critical for maintaining high performance at the system level. As was identified in the preliminary analysis of possible generator structures (presented above), in order to achieve 14% efficiency the contact resistance should be 1.0 $\mu\Omega cm^2$ or lower at the operational temperature of the interface. Even lower contact resistance values, on the order of 0.1 $\mu\Omega cm^2$, are beneficial for the higher efficiency TEG proposed for Year 2 Option; mostly due to the fact that some of the high performance TE materials will be in the form of thick films.

BSST has recently funded an effort at JPL to develop a structurally strong, low contact resistance, metallization solution for high temperature TAGS material. In the course of this study, a reliable, fast turnaround measurement system for electrical contact resistance was built. In this apparatus, a sharp Niobium probe is scanned across a polished face of TE material and metallization layer. Scan step resolution is below one micron. The resistance between the probe and the bulk electrode at the end face is measured as a function of probe position. Knowledge of the sample geometry allows for extracting the contact resistance value of each interface traversed by the probe.

Figure 2 shows the resistance measurement results that were obtained with this scanned probe apparatus for TAGS terminated with Tin Telluride and Iron. The data shows that the contact resistance was less than 2.0 $\mu\Omega cm^2$, which satisfied the goals of that program.

BSST's intention was to keep this measurement setup intact and available for ongoing development efforts with other thermoelectric materials and metallization systems. The same equipment will be used to measure the interfacial contact resistance within a segmented TE stack as required in this program.

BSST continued to work with material developers to assess the quality of existing metallization solutions, and if needed, assist them or take on the responsibility of providing appropriate metallization. BSST also explored developing relationships with service providers, possibly outside of the TE industry, to develop specialized or unconventional metallization solutions. That effort continues.



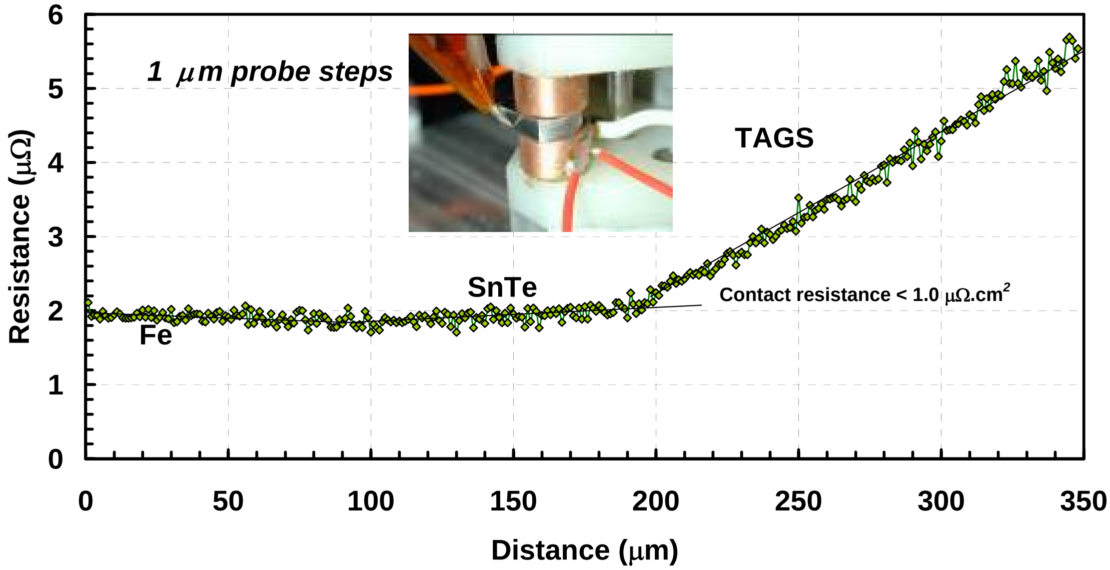


Figure 2. SEM micrograph of low contact resistance metallization of TAGS and the results of resistance measurements using a scanning probe. A sharp Niobium probe is scanned across TE material and interface while measuring the resistance between the probe and an end-face electrode of known area.

The interfacial bonding needs of the thermoelectric application are often unique compared to other industries. In the case of segmented materials, the processing temperature of the bonding step can not exceed maximum limits allowed for the low temperature side of segmented stack; this creates limitations on the choice of bonding technique and requires creative solutions to be developed.

Possible approaches include:

- brazing,
- diffusion bonding,
- soldering,
- reactive nanofoils (e.g. bonding approaches developed by Reactive NanoTechnologies, Inc. to address the bonding needs of microelectronics industry), and
- amalgams/diffusion hardening alloys.

Potential processes were evaluated by BSST for contact resistance properties, mechanical strength, void formation, and thermo-cycling stability, as required to meet program goals.

Thrust Area 4: Reduction of External Interfacial Losses

The fabrication of stable and durable junctions between TE elements and external electrical and thermal circuits has proven to be very complex and often vexing joining task. Such joints must have very low electrical and thermal resistances, be mechanically and chemically stable, and match the coefficient of expansion (CTE) of the adjacent TE material. The joints must maintain these characteristics over the operating temperature of the generator and provide sufficient durability to meet prototype functionality requirements. At a later stage, other criteria, including thermal cycling durability, toxicity, and cost, become important.

BSST and its parent, Amerigon, have very extensive experience in the definition, analysis, and engineering of these characteristics since they affect commercial viability of TE devices. Over 4,000,000 TE systems in daily service have been designed, specified, and qualified to meet performance demands in cooling and heating usage. While this project was underway, BSST was preparing power generation systems to operate in the same user environment, and as a result, was actively developing designs and material systems with reduced external losses.

BSST has performed extensive durability tests on TE power generator components and subsystems for the referenced DOE program and for major vehicle manufacturers. Typical test results for thermal interfacial stress as a function of the number of temperature cycles, and for different peak-to-peak temperature differentials (ΔT) are shown in Figure 3. The purpose of the tests was to determine endurance properties of the low and high temperature side of a Bi_2Te_3 generator stage, for various interface materials in a TE array.

In these tests, constant heat was applied to the hot side of each TE couple using a resistor, while the cold side was attached to the heat sink maintained at close to ambient temperature. A temperature versus operating cycles inflection point indicates an onset of a failure.

From the test results, criteria have been developed for thermally induced interfacial shear stress limits as a function of durability requirements. This knowledge base and its extension through other programs, as needed in the proposed program, will lead to design criteria for both the demonstration generator design and the development of the underlying interfacial systems. In our studies, as a part of this program, BSST pursued the evaluation of interface bonding designs that meet the program durability criteria including liquid electrical interface systems (to eliminate CTE induced interfacial stresses), diffusion, amalgams, and reactive chemical bond systems.

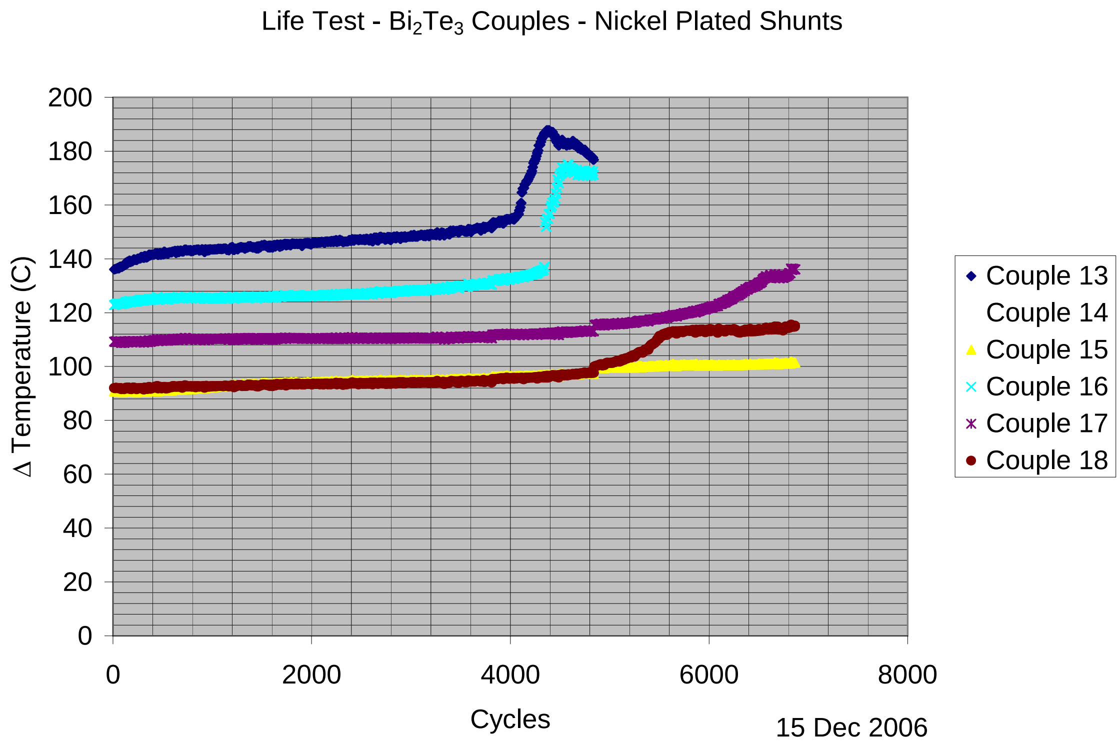


Figure 3. Thermocycling and durability test results of TE materials and shunt assemblies designed for low temperature Bi_2Te_3 TEG. Heat was applied to the hot side of couples using Joule heating of a resistor, while the cold side was attached to a heat sink maintained at close to ambient temperature. Each cycle lasted 90 seconds. The maximum temperature reached by the hot side during the cycle was recorded. Rising temperature indicates development of a failure.

Develop and Characterize Bonding/Interface Solutions on the Hot Side

CTE incompatibility can be a severe issue with TE systems. As can be seen from Figure 4, the rate of thermal expansion of TAGS goes through an abrupt slope change at about 220°C, making the CTE match very difficult over the TAGS operating temperature excursion of ambient to 500°C. BSST had and still has promising material systems for TAGS over this temperature range under development with JPL, enabling this effective but difficult material to be used in BSST TEGs. Other high performance materials, such as LAST and Skutterudites, especially in combination, were expected to offer somewhat similar challenges. Other innovative bonding solutions may need to be developed to fulfill requirements imposed by this program's goals.

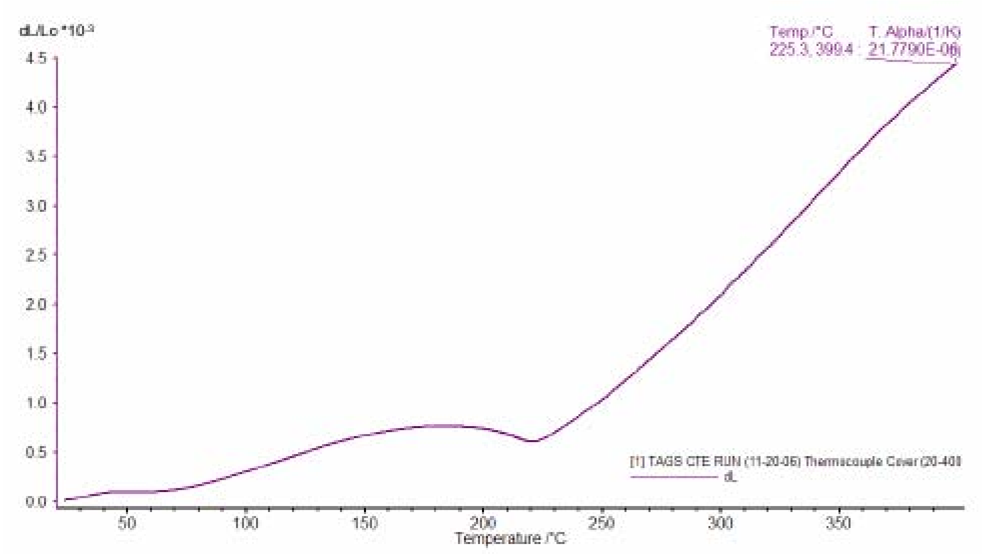


Figure 4. Coefficient of thermal expansion of TAGS material, as a function of temperature, as measured by JPL under a BSST-sponsored effort. Notice the abrupt change of the curve around 220°C.

Project Achievements

Year 1

In the initial year of this project, a worldwide survey of potentially high performance thermoelectric materials was conducted. Promising materials were sourced, tested and evaluated. A subset of the materials sourced was selected for use in the 14% TEG demonstrator. In addition, potential TEG architectures and construction methods were defined and evaluated against the criteria of yielding durable and reliable demonstrator units with at least a 100 cycle operating life. This progress in Year 1 created the foundation upon which a nominal 14% TEG demonstrator was fabricated, assembled, tested, and evaluated during the current year, FY2009.

Year 2

BSST's primary efforts during this period were to select the best available TE materials set from available materials for assembly and use in building a 14% efficiency TEG demonstrator, to design and build the TEG demonstrator itself, and to conduct a initial number of periods of TEG demonstrator operation to obtain TEG performance data. Material samples from an increasing number of sources have been obtained and tested, while additional samples continue to be sought from promising sources. Many of the samples obtained demonstrated problems with physical integrity, metallization, or yielded test results significantly different from those of the supplier. As a result, much of the material assessment work during this period consisted of ongoing coordination with material suppliers to reconcile testing issues, or to obtain samples more representative of the suppliers' claims or with improved physical integrity. Through the end of the project's Period of Performance, no samples demonstrated all of the breakthrough performance being sought.

Despite this status, BSST developed a TEG demonstrator design based on continued work on reduction of interfacial losses outside of a TE stack combined with a design direction based on system modeling. This design has the potential to produce a TEG that will perform near or at a level of 14% efficiency in a best case, but is not expected to fully meet Base Year requirements until better performing materials have been sourced and incorporated into the system. A set of known materials, though several are considered experimental, were selected for use in this demonstrator, based on known properties and BSST modeling results. Preparation of the TE materials, as well as fabrication and sourcing of TEG demonstrator components was carried out. In addition, test equipment including hardware and software to manage the demonstrator and capture performance data was designed and assembled.

Once the demonstrator equipment set including the TEG was assembled, calibrated, and configured for operation, the generator was operated over a number of discreet periods, with the operation within each period consisting of a discreet experimental run. Due to an unanticipated limitation of the heat source for the generator, the maximum operating temperature achieved during the experimental runs was 600°C rather than the target temperature of 700°C. During these experiments, the maximum power output observed was 9.8W versus the project target of 20.0W. The maximum efficiency observed was 8.9% versus the project target of 14.0%.

As previously mentioned, it was known that the material set used for this TEG demonstrator did not have the capability of supporting the achievement of 14% efficiency or 20W. The set was expected to achieve power generation of 11.5W based on testing of the component TE couples incorporated in the demonstrator. Evaluation of the factors contributing to this underperformance was undertaken. Attention was placed on internal resistances within the generator, interfacial resistances within the segmented thermoelectric elements, and on obtaining a heat source that will provide a consistent heat to the generator at 700°C. In addition, new thermoelectric materials that promise improved performance over those used in this TEG were sourced and evaluated. They were to be incorporated into the next TEG demonstrator build along with design improvements that prove to reduce internal TEG and interfacial TE segment resistances.

TEG Development and Demonstration Progress Achieved

Thermoelectric generator efficiency is one of the key metrics for assessment of technology viability in particular applications. The objective of the that was able to be undertaken in the project was to design and build a thermoelectric generator with 14% efficiency with a hot side temperature of 700°C and a temperature gradient of 670°C. In this work, efficiency is defined as the ratio of the electrical power output of the TE generator and the power input into the generator to maintain the temperature differential across the TE element. So to build a high efficiency generator, one needs to maximize the TE power output, minimize thermal and electrical losses and optimize the utilization of the heat input into the generator.

Figure 1 shows predicted impacts of major loss mechanisms on the generator efficiency. These simulations are specific to the generator design described further in this article. Relative contributions of different loss mechanisms are typically depending on the generator design and construction, however the individual loss mechanisms depicted in Figure 1 are present in any thermoelectric generator.

Figure 1 shows that to reach a goal of 14% generator efficiency with current design, it is necessary to start with an intrinsic material efficiency exceeding 16%. In the context of this project, the intrinsic, or ideal, material efficiency is defined as the power output of the TE material divided by the heat input in the TE material in the absence of any loss mechanism.

One can easily observe that with multiple complexities of extreme operating conditions and integration challenges of diverse materials it is critically important to accurately design individual couples and overall system achieve high efficiency.

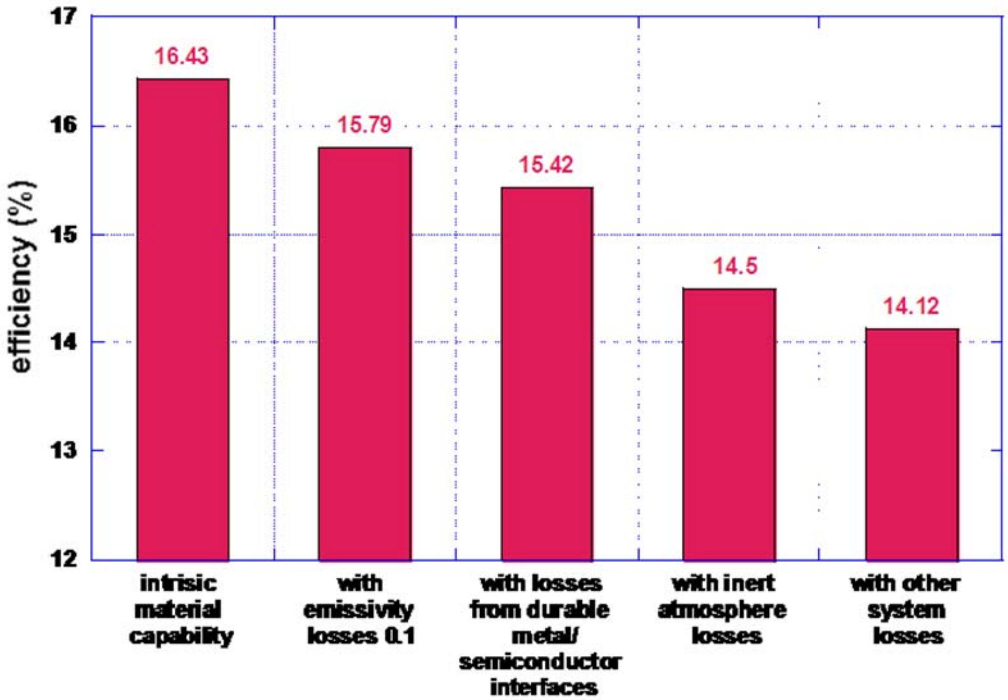


Figure 1. Design-specific impacts of individual loss mechanisms on the generator efficiency, predicted for the subject generator.

Couple-level testing

After carefully selecting and modeling the performance of the segmented thermoelectric elements, segmented couples were fabricated and performance was evaluated before building the generator. Similar modeling of segmented TE couples was previously described by D.T. Crane[i,ii]. To maximize the power output at the target hot side temperature of 700°C, a three segmented element design was used in this work. Bismuth telluride was used at the low temperature end, lead telluride and TAGS were used at the intermediate temperature and Half-Heusler (HH) materials were used at the hot end. The lengths of the various components that make up the segments were optimized through modeling, and the segmented couples were fabricated to validate the models. A variety of couple-level testing was performed on the segmented legs at various temperatures in a glove box in Argon atmosphere.

For both p and n legs, the cross-sectional area of the elements is 3x3 mm. The n-leg is constructed from segments of Bi_2Te_3, PbTe and HH, with 1.6 mm, 3 mm and 3.3 mm lengths respectively for a total segment length of 7.9 mm. The p-segment is constructed from the segments of Bi_2Te_3, TAGS and HH, with 2.3 mm, 2.6 mm, and 2.9 mm lengths respectively for a total segment length of 7.9 mm.
Figure 2 shows the performance data at different temperatures, as well as the simulated results from the modeling work for three such couples connected in parallel. At 662°C hot side temperature, the highest

hot side temperature at which BSST was able to perform the measurements on this assembly, the peak power output is 1.275 W for three couples or 0.425W for an individual segmented p-n couple. The cold side was maintained at 20°C.

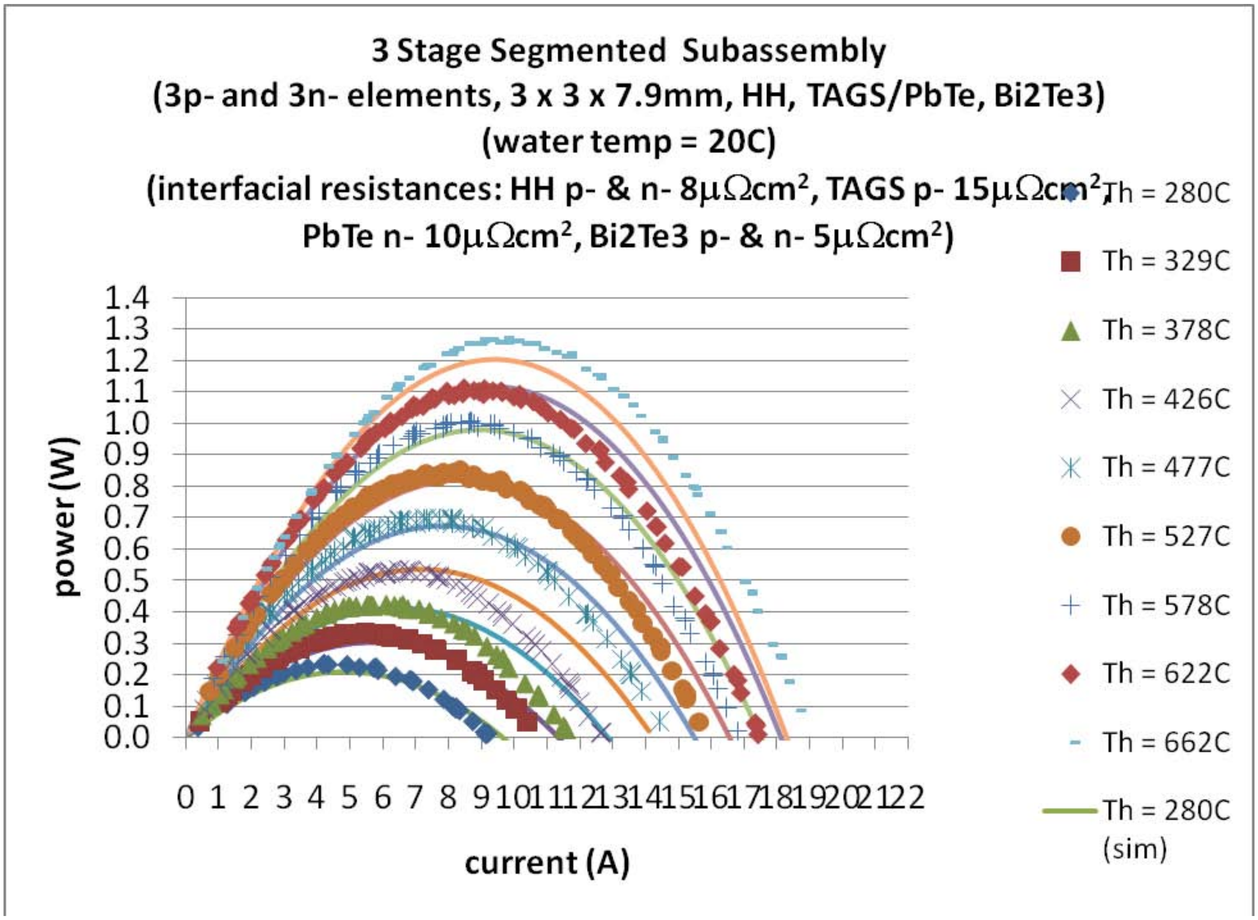


Figure 2. Power curves from three couples assembled in series. Each element consist of three segments: p-Half Heusler/TAGS/Bi_2Te_3, n-Half Heusler/PbTe/ Bi_2Te_3, element cross-section is 3x3 mm, overall height is 7.9 mm. Cold side is maintained at 20°C.

Generator design and testing

Since the objective of this work was to demonstrate high thermoelectric generator efficiency, several design considerations were made to maximize the heat utilization (minimize heat losses) and to enable efficient heat transfer from the heat source to the TE elements. Figure 3 shows a schematic cross-section view of the generator, and Figure 4 shows the schematics of the TE assembly at the cold and hot ends.

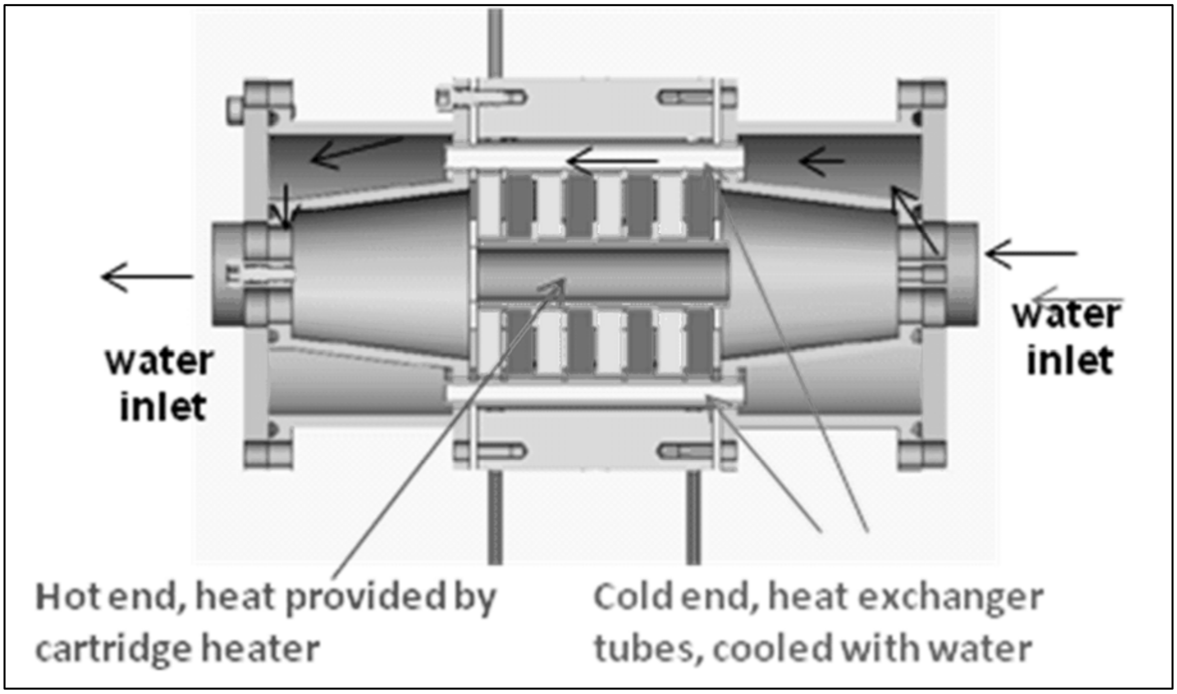


Figure 3. Axial cross-section of a water-cooled, cylindrically symmetrical generator with segmented TE elements located radially around an axial heat source.

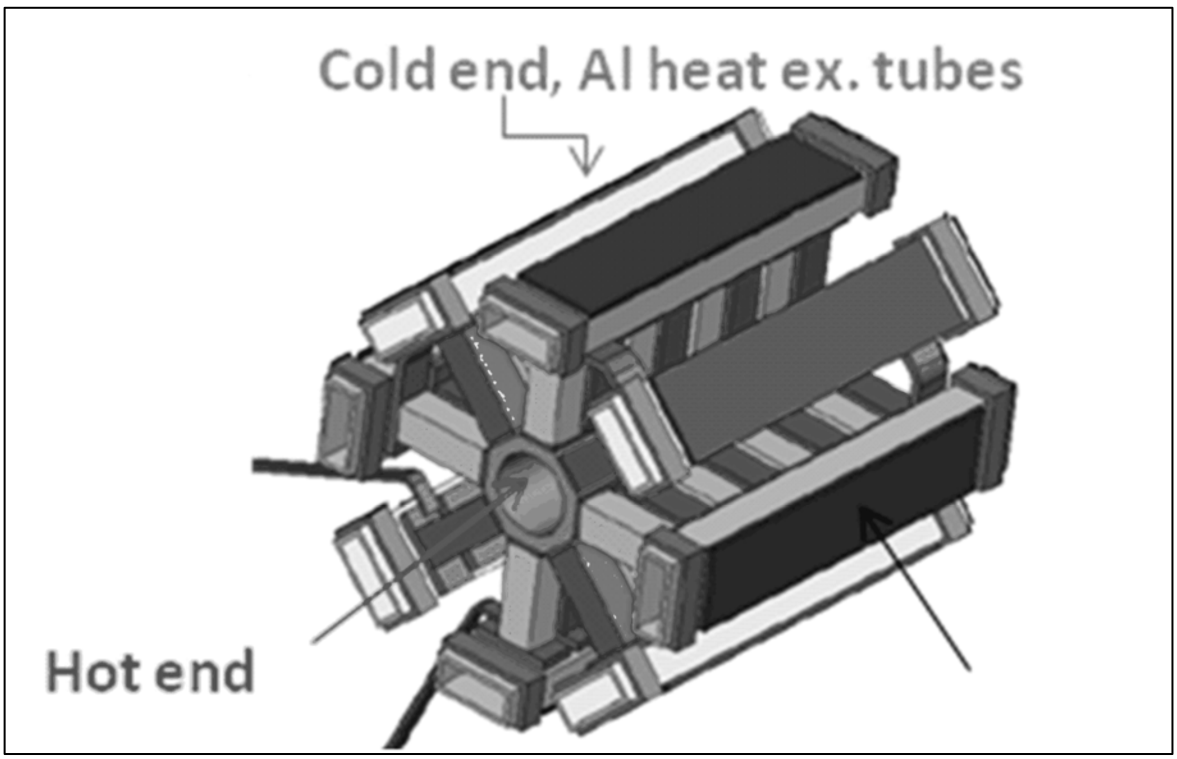


Figure 4. Construction details of the cylindrically symmetrical generator.

Located around the axis, the hot end of the generator consists of an octagonally shaped ceramic tube made from aluminum nitride (32mm long, 3.2mm face width and 6.4 mm diameter hole). The center bore accommodates an electrical cartridge heater to provide heat input. The use of electrical cartridge heater allows us to measure the heat input into the generator accurately for efficiency calculations. Copper shunts were brazed to the AlN tube and segmented TE elements were soldered to the copper shunt. On each face of the octagon, 4 p-n couples were connected in series for a total of 32 p-n couples in the generator that are connected in series. At cold end the copper shunts were joined to the internally finned, anodized aluminum heat exchanger tubes, through which water is circulated for cooling. The TE assembly is housed in an anodized aluminum tube with set screws. Figure 5 shows a picture of the assembled generator. The internal volume is filled with continuous purge of Ar gas. Such purge allows for operation of the device in a regular laboratory environment, eliminating the need for a glove box.

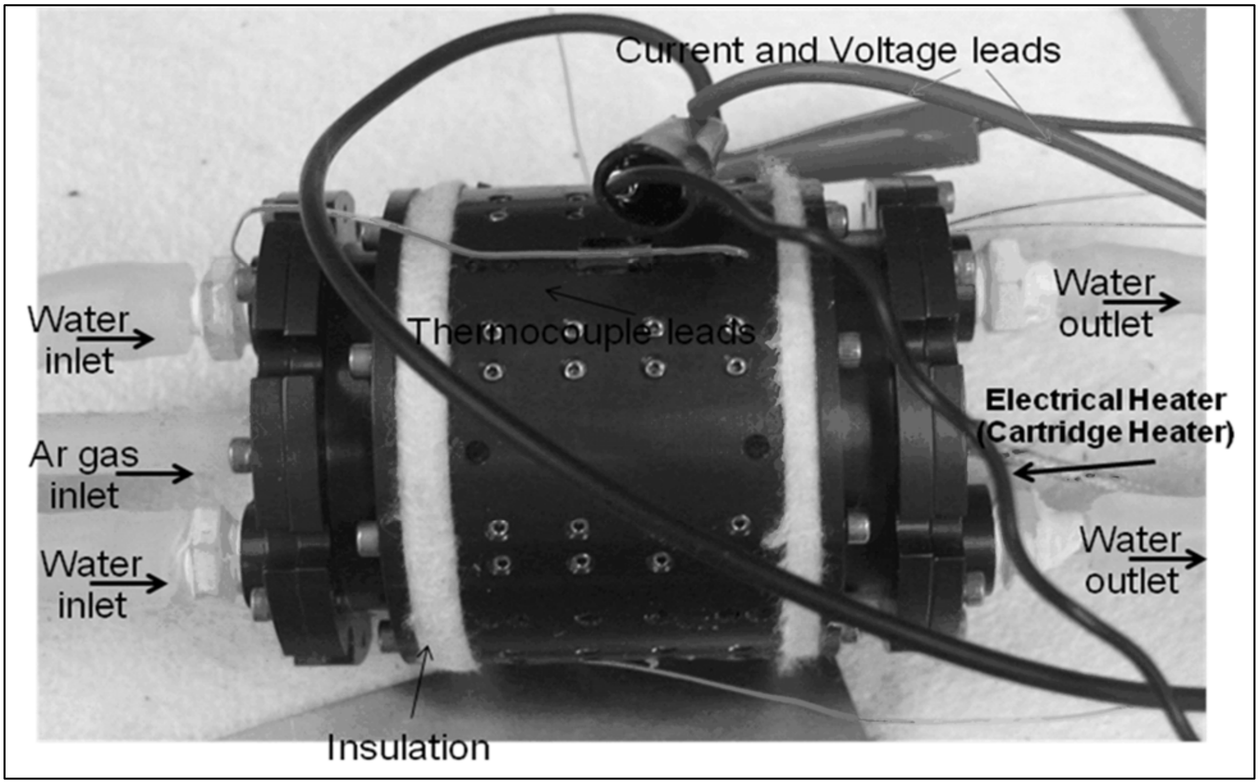


Figure 5. Fully assembled generator.

Figure 6 shows further details of the internal view of the assembled generator. The radial symmetry of the device allows for maintaining the TE elements under compression in the radial direction.

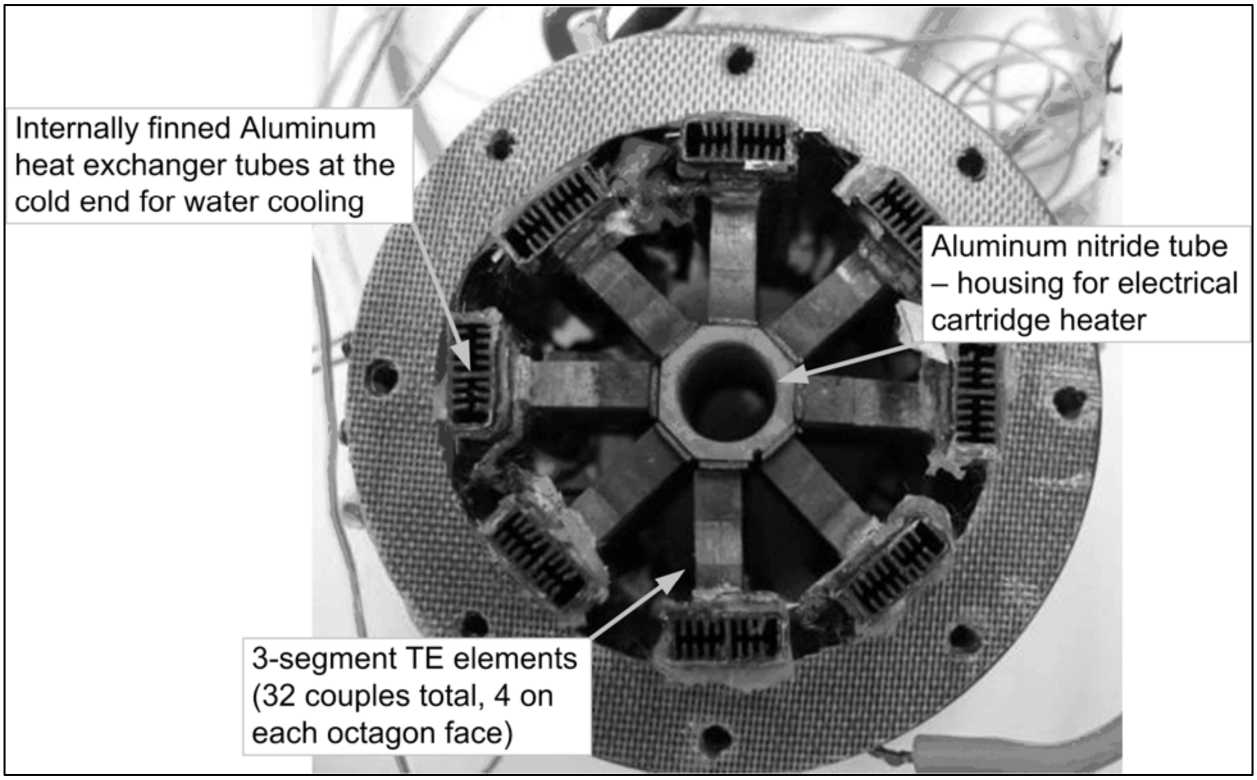


Figure 6. Internal view of fully assembled hot and cold sides of the generator separated by segmented TE couples.

Typical performance data of the prototype generator is shown in Figures 7 and 8. Figure 7 shows the open circuit potential of the generator at various temperatures and Figure 8 shows the power output at 600°C. The measured open circuit voltage of 8V at 600°C matches well with the design target for the three segmented p-n couple used in this design. The peak power output at 600°C is 9.8W, which is slightly less than the projected power output of 11.5W based on the couple level testing derived from data shown in Figure 2. The most probable reason for this discrepancy is the higher internal resistance of the fabricated generator made from 32 couples compared to the resistance of individual couples.

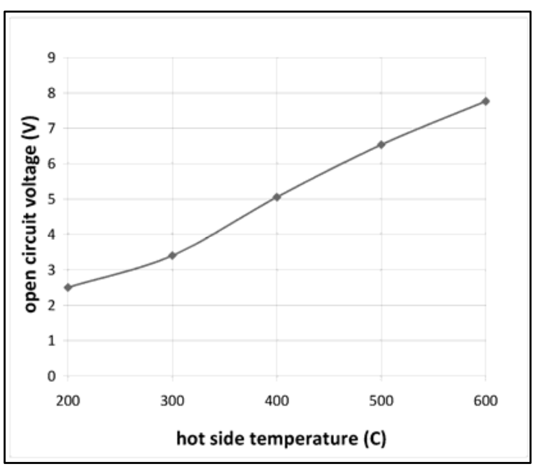


Figure 7. Open circuit voltage of generator as function of hot side temperature.

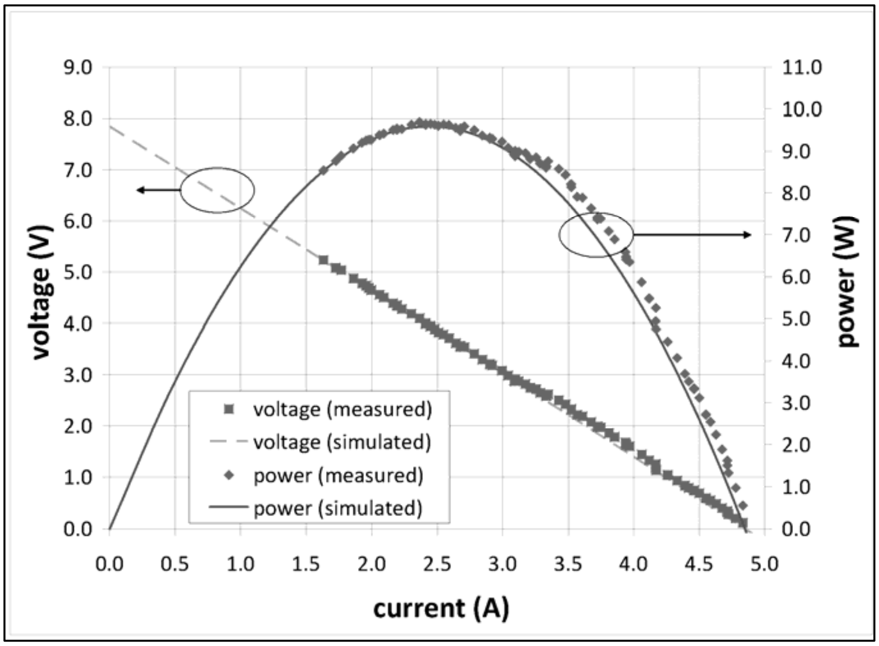


Figure 8. V-I and power curves for the cylindrical generator operated at 600°C hot side and 20°C cold side.

Finally, addressing the issue of the generator efficiency, Figure 9 shows the power input into the cartridge heater to maintain the TE generator at various hot side temperatures. Maximum observed efficiency of this prototype generator at 600°C is 9.8W/110W = 8.9%. The target efficiency of the generator at 700°C is 14%. BSST was not able to evaluate the generator performance at 700C due to difficulties with the electrical cartridge heater power density. We also experienced increased internal resistance of the generator with repeated testing and thermal cycling. The causes of this increase in contact resistance remains under investigation.

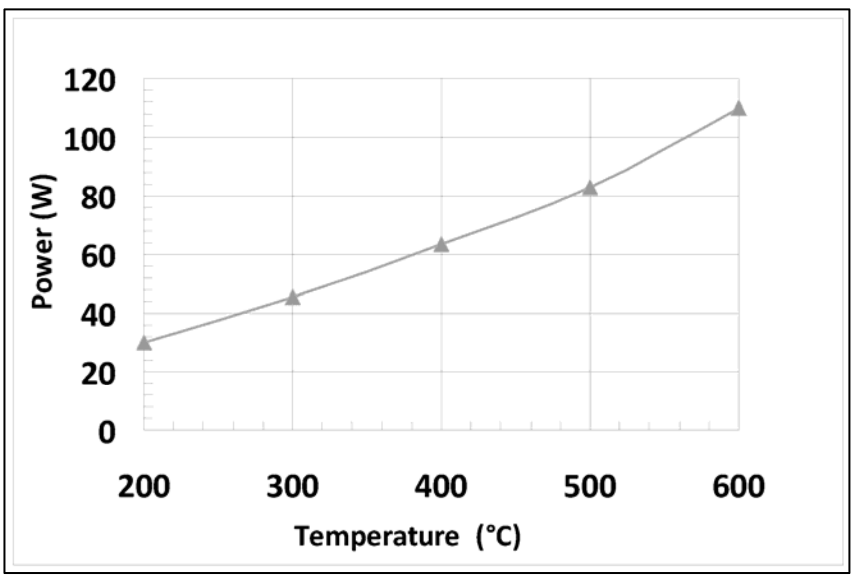


Figure 9. Electrical power input into the cartridge heater that serves as the heat source of the generator. The powers are plotted for different hot side temperatures of the TE couples.

End of Project Efforts

Completion and evaluation of the development and performance of the initial TEG demonstrator marked the end of effort in this project. With the agreement of the Program Officer, the search for and evaluation of emerging TE materials with promise of much increased performance over state of the art materials had been extended in scope and time substantially beyond that established in the project proposal. This course of action was taken both because sought-after advanced TE materials were emerging much more slowly than anticipated, and because several organizations were finally beginning to produce more promising results, but were still early in the process. It was hoped that some high performance TE materials that could support the project goals would have become available within the project's timeframe, allowing at least the 14% generator goal to be achieved. While significant progress was made toward this goal in TEG design, TE couple and device fabrication and assembly, and in assessment and selection of materials, the initial goal could only be partially met without significant additional progress in TEG design and assembly methods beyond the project's funding and without the emergence of availability of TE material with performance characteristics beyond that of currently available materials.

Envisioned Actions to Continue Pursuit of Project Goals

Near term, were the project continued, the actions envisioned to pursue demonstration of the TEG at 14% efficiency or better are those continuing on the path established in this program. A fundamental test setup improvement to be taken would be to source new cartridge heaters with high power density to test the generator at 700°C. Other tasks would include investigating the causes of increased contact resistance with repeated testing and thermal cycling of the generator. Material selection and design for the generator would be optimized based on these investigations. New thermoelectric materials with high performance would be sourced and their performance would be evaluated at the couple level. If such evaluation was promising, such materials would be integrated into the next generator build for improved performance. Packaging and insulation effects to further reduce the losses, and thus improve efficiency, would also be pursued.

References

i. D.T. Crane et al., Journal of Electronic Materials, v. 38 (2009) 1375
ii. D.T. Crane et al., Journal of Electronic Materials, v. 38 (2009) 1382